Collisional Stellar Dynamics, Gas Dynamics and Special Purpose Computing

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1 Abstract

Challenging stellar dynamical problems, such as the study of gravothermal oscillations in star clusters, have in the past initiated the very successful building of GRAPE special purpose computers. It is discussed, that present day tasks such as the formation and evolution of galactic nuclei with one or more massive black holes and the coupled stellar and gas dynamical processes in the formation of nuclei and star clusters, demand a new kind of hybrid architecture, using both GRAPE and a reconfigurable logics board called RACE. For such a system we have developed first implementations and floating point performance studies in the case of the SPH algorithm (smoothed particle hydrodynamics), which will be of great advantage for SPH modelling and also for direct N-body simulations using the more efficient Ahmad-Cohen neighbour schemes.

2 Historical Introduction

German-Japanese cooperation in stellar dynamics dates back for at least about two decades. One of its early highlights are the visit of D. Sugimoto as a visiting Gauß-Professor at the university observatory in Göttingen, Germany. At that collaboration, mainly with E. Bettwieser on the German side gravothermal oscillations of globular star clusters were detected using a gaseous model[8]. The first author of this paper witnessed this as a freshman student in Göttingen. Subsequently a discussion arose whether such oscillations exist in real N-body systems; that question was a main motivation for the construction of GRAPE special purpose computers at the University of Tokyo in Japan[20, 26]. Their use made it possible to demonstrate that gravothermal oscillations are indeed present in real N-body systems[18]. Subsequently GRAPE became an important computing equipment for many scientists working in stellar and galactic dynamics, also in Germany (see informations in `www.astrogrape.org`). In ongoing cooperative projects funded by the German and Japanese science foundations the first GRAPE computers began to work in Germany at the University of Kiel since 1993 (later moved to Astronomisches Rechen-Institut, Heidelberg) and at the two Max-Planck institutes (MPIA Heidelberg, MPA Garching). Presently, MPIA and ARI in Heidelberg, the University of Mannheim, Germany, and the University of Tokyo cooperate on the development of hardware and software suitable to tackle new challenges of modelling galactic nuclei, galaxy formation and evolution, and globular clusters. In the following a brief introduction is given into a selected sample of our astrophysical tasks. Finally some new ideas for the use of special purpose hardware are presented.

3 Gravothermal Star Clusters

Gravothermal Systems are those stellar systems in which the two-body relaxation has played an important role in their lifetime. It can approximately be modelled as a heat conducting gas[12]. Astrophysical examples are dense (globular) star clusters and dense cusps in galactic nuclei around supermassive black holes. On the contrary many stellar systems such as galaxies as a whole are collisionless. Gravothermal systems are very difficult to study in direct numerical simulation, because most pairwise gravitational interactions have to be followed with high accuracy. The effect of gravothermal oscillations found by gas models[8] could only 12 years later be seen in sufficiently large direct N-body simulations[18]. The search for gravothermal oscillations was one of the driving ideas to build a fast special purpose computer called GRAPE (**Gra**vity **P**ip**e**) [20, 26]. The dominant N^2 dependent part of the algorithm (pairwise force calculations) was mapped on it, using special arithmetics, pipelining and parallelisation. Still today we have not yet reached a final understanding of how globular clusters evolve; present studies try to improve theoretical modelling based mainly on the Fokker-Planck approximation and to compare its results with direct N-body models on rotating clusters, tidal fields and tidal shocks, a large number of primordial binaries, the influence of stellar evolution and the final fate of its remnants. The citation list is exemplary, but not exhaustive [5, 9, 11, 13, 15, 16, 27].

4 Galactic Nuclei with Black Holes

In the course of the merger of two galaxies their central black holes may ultimately coalesce, emitting in the very last phase strong gravitational radiation[6]. During the early stages of the galaxy merger, the stellar component will form a dense core through violent relaxation within a rather short timescale. After that, the two supermassive black holes move through the stellar component with a velocity similar to the initial relative motion between the two galaxies. From this moment on, both massive bodies will feel dynamical friction. This friction leads the black holes to the newly-formed galactic center, while the frictional force becomes more efficient with increasing density. Through this process, the black holes must inevitably ‘find’ each other and form a binary system[19].

After being bound, the binary hardens (increases its binding energy) further through dynamical friction. At a certain binding energy dynamical friction between each black hole and the stellar system becomes inefficient. Close encounters and resonant three body interactions then provide further hardening for the binary. The most efficient process for binary hardening in this stage are those scatterings, after which the single stars gain very large velocities in a three body encounter with the black holes (superelastic scatterings). If the binary black hole centre of mass were fixed in the cluster, this process could evacuate the surroundings of the binary from suitable stars for further hardening, the hardening would stall. We observe in our simulations, however, strong recoils of the binary centre of mass due to the superelastic scatterings, so the hardening does not stall[14].

This is another challenging problem for our present-day software and hardware to simulate stellar systems. New hybrid codes[14] including the recently developed parallel direct N-body integrators[1, 2, 24] model a galactic nucleus containing two massive black holes using up to 128k single particles. With the recent GRAPE6 special purpose computer a model of three black holes in a nucleus of 512k particles has been simulated (Makino 2001, pers. communication). The shrinking of the black hole binary has to be followed until a phase where gravitational radiation sets in and a massive black hole merger occurs.

One of the most important parameters is the final eccentricity of the black hole binary, because the gravitational radiation induced merger depends critically on it. We present in

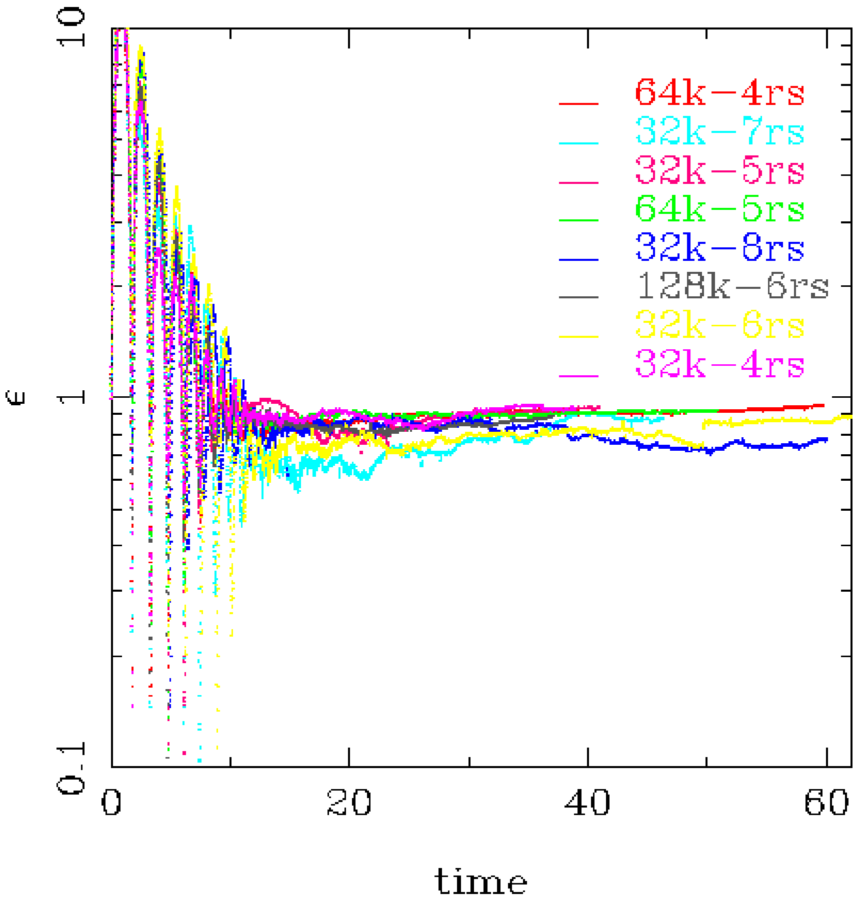

Figure 1: Development of the orbit eccentricity ε of the black hole binary as a function of time in model time units (left), for a sequence of runs with different N, as indicated in the key. Note, that if the binary is not yet bound there are formally values of $\varepsilon > 1$. Different particle numbers are indicated, and for curves with the same N the statistical particle representation of the initial model was varied. Circular orbit is $\varepsilon = 0$.

Fig. 1 an example of the time evolution of the eccentricity of the black hole binary from the work of[14]. A movie showing the black hole binary forming and moving in the galactic nucleus can be found under
`ftp://ftp.ari.uni-heidelberg.de/pub/staff/marc/MPEG/simulation600.mpeg`.

In the final hardening phase due to superelastic three body encounters the eccentricity of the black hole binary remains at a fairly large value (around 0.7), which is very interesting because it decreases the time scale for gravitational radiation merger of binary black holes dramatically, and thus increases our chances to detect gravitational radiation from such events via the planned gravitational radiation detector satellite LISA. In a system with three black holes Makino finds even larger eccentricities than 0.99.

5 Gas Dynamics, Galaxies and Star Clusters

While in certain evolutionary phases dynamics of star clusters and galactic nuclei is predominantly determined by stellar dynamical processes (they can be seen to first order as a system of gravitating point masses) their formation process is necessarily linked to a complex gas physics, including star formation, cooling, feedback processes and possibly even exotic events such as gas production by stellar collisions or star-gas interactions in dense star-gas systems. Again we have here for brevity selected a few exemplary references for the interested reader which cannot be exhaustive in any way[3, 7, 10, 17, 22, 23]. Many of the cited papers use a particle approach (smoothed particle hydrodynamics[21]) to describe the dynamics of coupled gas-star systems; it is assumed that both stars and gas are represented by particles moving in a self-consistent gravitational potential, but the gas particles are subject to additional non-gravitational forces due to the gas physics.

6 Implementation Issues - GRACE

For astrophysical particle simulations including self-gravity, the determination of the full gravitational potential at each particles position is usually the most expensive step in terms of computational time required. This step, which is very efficiently done by the special hardware GRAPE, requires computational time $T = \alpha N + \beta N^2$, where β is a time constant depending on hardware and on the algorithm (how many flops per individual pairwise force calculation). The first term linearly dependant on N represents costs for advancing the particles and communication, if GRAPE is used. The idea of GRAPE is based on the strategy to reduce β by hardware for the dominant term as much as possible. The most advanced N-body algorithms, however, use an Ahmad-Cohen scheme, where the short- and intermediate range force (neighbour or irregular force) is updated more often than the long range (regular) force[1, 2, 24]. If on average for every γ irregular force computations one regular force is computed the algorithm scales as $T = \alpha N + \delta N \cdot N_n + \beta N^2/\gamma$. Here N_n is a typical neighbour number which is small compared to N. Such algorithm has been well implemented on general purpose parallel computers[24, 25], but it does not work efficiently on the present GRAPE special purpose hardware. It is interesting to note that the second scaling also holds for high-accuracy codes using the SPH algorithm. The difference to pure N-body is that δ becomes larger, since SPH forces require of order 100 flops per pair of neighbour particles instead of only about 20 for the gravitational neighbour force only. Also in many existing codes the leading term is $\propto N \log N$, instead of N^2, because a TREE algorithm is used for the long range force[4]. In the challenging applications mentioned above the high accuracy N^2 algorithm will be required at least for a large subset of particles for accuracy reasons in gravothermal gas-star systems. Also the direct method is more advantageous for parallelisation and the use on GRAPE computers. Whether the TREE or direct force computations are used or not, the newly proposed hardware concept will be useful in both cases. The development of suitable algorithms for very large particle numbers and keeping a certain high degree of accuracy for the gravothermal systems is subject of present and future work.

Here we propose a new hardware architecture called GRACE (**GRA**PE and R**ACE**), which combines the very fast GRAPE special purpose hardware with another hardware based on reconfigurable logics RACE (intermediate speed), both coupled via a common PCI interface to a host workstation.

The Fig. 2 plots a theoretical estimate to show, how a well balanced performance of the three components GRAPE, RACE and host workstation yields best performance. Just as an example we use for that picture an assumed performance of 1 Tflops for the GRAPE subsystem, 5 Gflops for the reconfigurable RACE subsystem, and 50 Mflop for the host workstation. In

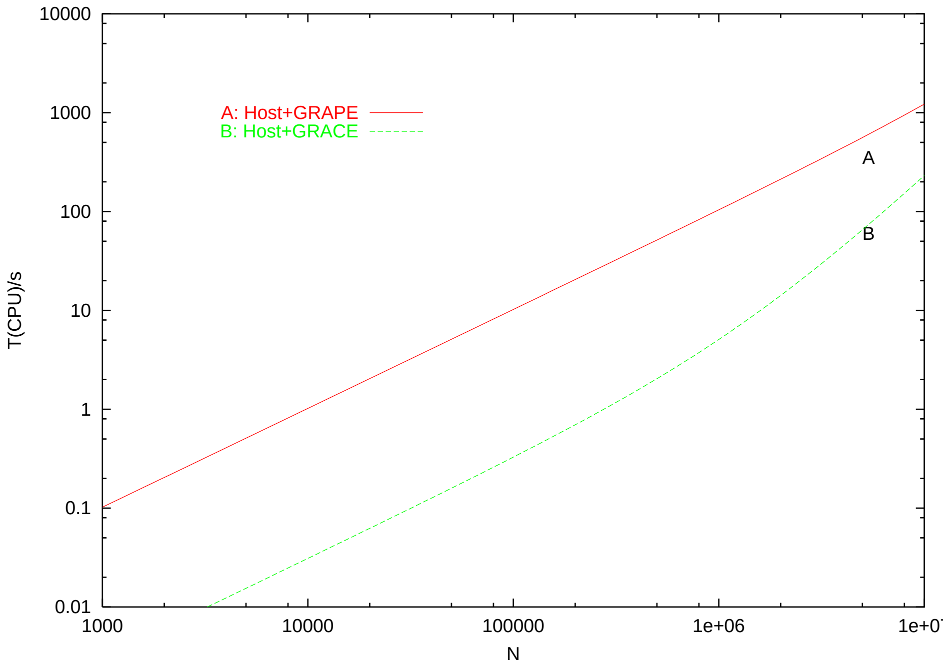

Figure 2: Estimated CPU time per step for a host system with GRAPE (A), and the combination GRACE between GRAPE and RACE (B). Assumed performance is 50 Mflop for the host, 1 Tflop for the GRAPE, and 5 Gflop for the RACE component, see main text.

presently ongoing work (Lienhart, G., Wetzstein, M., et al., in preparation) a full loop of the SPH algorithm has been implemented on the available logic resources. The existing implementation works on the present hardware with roundabout 5 Gflops in floating point performance, as used in the plot. The interested reader can find more information on the reconfigurable RACE board under
`http://www-li5.ti.uni-mannheim.de/fpga/?race/`
and on the SPH implementation on it under
`http://www-li5.ti.uni-mannheim.de/fpga/?astro/`. Apart from the pure speed-up of such a combined GRACE system as compared to a pure GRAPE system such a new hybrid architecture has strong further potential advantages. First, it can overcome the host bottleneck for all kinds of N-body-SPH applications. Second, it can make the efficient use of GRAPE systems possible for the more intelligent neighbour schemes in direct N-body models. Third it allows flexibility where it is required: for the short- and intermediate range forces (softening, non-gravitational forces due to gas or molecular dynamics). While the general idea appears very promising, the implementation in detail has still to be carefully examined, in particular the way how the different hardware components communicate and store data and neighbour lists, for example. This work opens a path for more integrated GRAPE and RACE systems in the future.

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